MOVING STRIATIONS IN ARGON GLOW DISCHARGE

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37

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PREFACE

In a direct current glow discharge having a positive column, oscillations are usually observed in tube voltage, tube current, and light intensity. These oscillations have been observed for many years, but were considered a matter of mere curiosity, or possibly an abnormal condition; and due to lack of adequate and precise instruments for study, very little information was available to explain their existence and behavior.

In recent years, however, due to the advances in technical fields and to military and industrial applications, the subject of gaseous discharge has assumed increasing importance.

This thesis describes work which was performed at the U.S. Naval Postgraduate School between September 1955 and May 1956, and is a continuation of studies made the previous year by Karge, Hooks and Oleson. It consists of additional observations of those oscillations and striations, and an attempt to correlate them with the most recent theories.

The writers wish to thank Professor S.H. Kalmbach, for his assistance, encouragement and guidance throughout this work; Mr. K.C. Smith, Mr. M.K. Andrews and OMC R. Moeller for their assistance. In addition, we wish to thank Professor N.L. Oleson, who, although absent on sabbatical leave, gave his encouragement, advice and inspiration by mail.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

INTRODUCTION

1. Summary

This thesis is a continuation of the experimental investigations of gaseous discharges, and in particular, the investigation of moving striations. It is essentially a continuation of the work of Karge, Hooks and Oleson (10). A study was made of phase differences of the fluctuations in tube voltage and electrode currents. Another study was conducted to determine if there were phase differences between the individual spectral lines produced by striations in the positive column. Both of these studies were made in an attempt to learn more about the mechanism producing these moving striations, and to correlate our observations with the recent theory of Donahue and Dieke (6), which is summarized in Section 4, Chapter I.

The fluctuations in tube current at the anode are in phase with current fluctuations at the cathode. Spectral intensity in the positive column decreases to zero between maxima. The maxima of spectral lines resulting from the same initial excitation potential occur at the same time in the positive column, but earlier in time than those lines having a greater initial excitation potential.

2. Characteristics of the Glow Discharge

When a gradually increasing voltage is applied across two electrodes in a gaseous discharge tube, only an extremely small current flows until the applied potential reaches a certain critical value called the breakdown potential. At this point the current increases by a large factor, possibly 10^8, and the discharge is accompanied by a characteristic

emission of radiation from the tube. Once started, the potential necessary to sustain this discharge is lowered. This discharge is termed a glow discharge, and is usually defined as a discharge with a relatively small current density (< 0.1 amp/cm^2) at the cathode, and a cathode fall of 50 volts or more, where the electrons are liberated from the cathode mainly by positive ions.

The value of the breakdown potential and the characteristics of the glow discharge are functions of the physical dimensions of the tube, and the pressure of the gas present. At atmospheric pressures, the discharge takes the form of a tortuous spark, and is essentially similar to lightning occuring in the atmosphere during a thunder storm. As the pressure is reduced, the breakdown potential becomes less and the conducting path becomes more diffuse. At a pressure of a few cm. of Hg., the glow will be uniform and occupy the entire tube. At a pressure of a few mm. of Hg., the glow will be made up of alternate dark and light regions. Starting from the cathode, there is a primary dark space termed the Aston dark space; then follows the cathode glow, which fades gradually into the cathode dark space; following this is the negative glow, which fades off diffusely into the Faraday dark space; then comes a long glowing region, the positive column, which sometimes exhibits stationary striations, but normally contains moving striations. Under certain conditions there may be an anode glow and anode dark space.

As the pressure is reduced, the breakdown potential again increases, and the cathode glow expands at the expense of the positive column, ultimately taking over the entire tube.

3. A Brief Summary of Moving Striation Investigations

The discovery of moving striations in gaseous discharges was made by Abria in 1843. A summary of the very early studies can be found in Thomson (16). Summaries of the more recent work are available in Loeb (11), Cobine (4), or Druyvesteyn and Penning (8). Early studies in the field were made by means of rotating mirrors or rotating cameras (2). Pupp (13) used a photocell in conjunction with a cathode ray tube to obtain a record of the fluctuations of light intensity caused by the striations. Sloane and Minnis (14) employed a mechanical shutter synchronized with the moving striations. Appleton and West (1), and Fox (9) made detailed studies of the electrical oscillations accompanying the moving striations. Donahue and Dieke (5,6,7), employing a photocell and oscillograph, have made the most significant advances in the field, and have presented a tentative theory explaining the mechanism of the moving striations.

Karge, Hooks and Oleson (10) developed additional techniques employing an electronic counter for instantaneous frequency monitoring and a dual beam oscilloscope to provide for simultaneous viewing of two wave forms. Stewart (15) has recently completed studies of glow discharges in rare gases excited by an audio frequency alternating potential, and has elaborated on the Donahue and Dieke theory.

4. Theory Explaining Moving Striations

The following theory of the mechanism of moving striations is that presented by Donahue and Dieke (6). There are two types of moving striations, positive and negative. Positive striations are concentrations of positive space charges moving toward the cathode with a certain definite velocity (in 12 mm argon, this velocity varies from 33 to 350

meters/sec depending on the tube current). Negative striations are concentrations of negative charges moving toward the anode with a considerably higher velocity (about 2000 meters/sec).

The classical theory indicates that the current at the electrodes suffer fluctuations in time of a statistical nature. Each of the electrons produced by a particular positive ion striking the cathode must produce 1/N ion pairs in the cathode fall for the discharge to be self sustaining, where N is the number of electrons emitted per positive ion. After passing out of the region of high field strength and losing energy in the negative glow, the primary and secondary electrons then travel into the positive column. The number of electrons passing any surface in the positive column per unit time is essentially constant, and hence, there is a steady current at the cathode and at the anode.

However, as pointed out by Donahue and Dieke (6), this theory is defective in that it does not explain the process whereby the electrons, after passing out of the region of large positive space charge in the fall space and losing a considerable part of their energy by excitation in the negative glow pass into the supposedly uniform field of the positive column. There is certain to be an accumulation of electrons in the negative glow for somewhere in this glow the sign of the total space charge must become negative. It is even possible that the electric field becomes negative here. Thus a trap would exist for the electrons around the negative glow. If these excess electrons in the negative glow are not removed, then the current delivered to the positive column would not be steady, but would decrease as the negative space charge in the negative glow increases and spreads toward the cathode. The field in the

cathode glow would then decrease, causing the current at the cathode to diminish, and presumably the discharge would be extinguished due to the critical nature of the cathode fall.

It is necessary, therefore, to arrest or stop this electron entrapment process before it has developed too far. Donahue and Dieke (6) feel certain that the positive striations provide the means of removing the excess electrons which have accumulated in the negative glow. When one of these striations preceded by a region of high field has come sufficiently close to the trapped electrons, the barrier will be lowered and the electrons will be released to travel in a burst toward the positive striation. This burst of negative charges is a negative striation. When the electrons leave, the effect is to increase the cathode fall causing greater emission at the cathode in the form of a negative striation, which travels across the cathode fall and meets the oncoming positive striation at the cathode side of the negative glow. Here a neutralization occurs and the process of electron entrapment begins anew, because the positive striation in the positive column has been neutralized by this time by the negative striation. The negative striation feeds so much charge into the positive striation that both striations stop, creating a plasma of low total charge density. Excitation of neutral atoms and emission of light decrease, and this positive striation ceases to be an agent for the removal of electrons. Once again the current decreases and electrons accumulate in the negative glow. However, another positive striation soon draws close to the first trapped pair, and will draw out the trapped electrons. This cycle is repeated until eventually the first positive striation becomes free so close to the negative glow that it

travels all the way to the cathode side of the negative glow where it is met by a negative striation from the cathode.

It should be noted that the cathode fall is never so much reduced that the process of ionic bombardment and electron emission at the cathode is greatly reduced. Actually these represent fluctuations which are only a small percentage of the total current. The negative glow never becomes dark and there is always a steady undercurrent of electrons through the positive column, but they are of low energy between positive striations and do not cause any excitation except during the periods when they are enhanced by a negative striation.

It should also be pointed out that the time of maximum current at the cathode is that instant at which electron emission is greatest due to the reduced negative charge in the negative glow; i.e., when a negative striation leaves the cathode. Donahue and Dieke (6) have observed this to be true.

In the positive column the negative striations travel or are passed from one positive striation to the next in moving toward the anode, each positive striation periodically releasing them from the one ahead of it. On the other hand, the positive striation travels toward the cathode between each entrapment.

The origin of the positive striations is not too clear, but they are observed to arise near the anode. They apparently always leave the anode at a time when the voltage across the discharge tube is a maximum. Apparently, after a positive striation moves away from the anode, the electrons traveling between this positive striation and the anode approach near the anode with continually increasing energy, until they have built

up a large cloud of positive ions by collisions with neutral atoms in front of the anode. This space charge shields the anode and the current drops until the positive space charge has built up far enough to be moved away from the anode by the mechanism of positive ion movement, which is described in the following paragraph. It thus becomes a positive striation and moves off toward the cathode until it meets a negative striation as explained earlier. This negative space charge is then released to the anode when the potential of the anode has risen high enough to draw it away.

The mechanism of the movement of the positive striations and the manner in which ionization takes place appear to be related in that the manner in which ionization takes place near a striation tends to cause a shift in the positive ion concentration toward the cathode. The configuration or distribution of ions and excited atoms, tends to preserve itself by moving in the direction of the cathode.

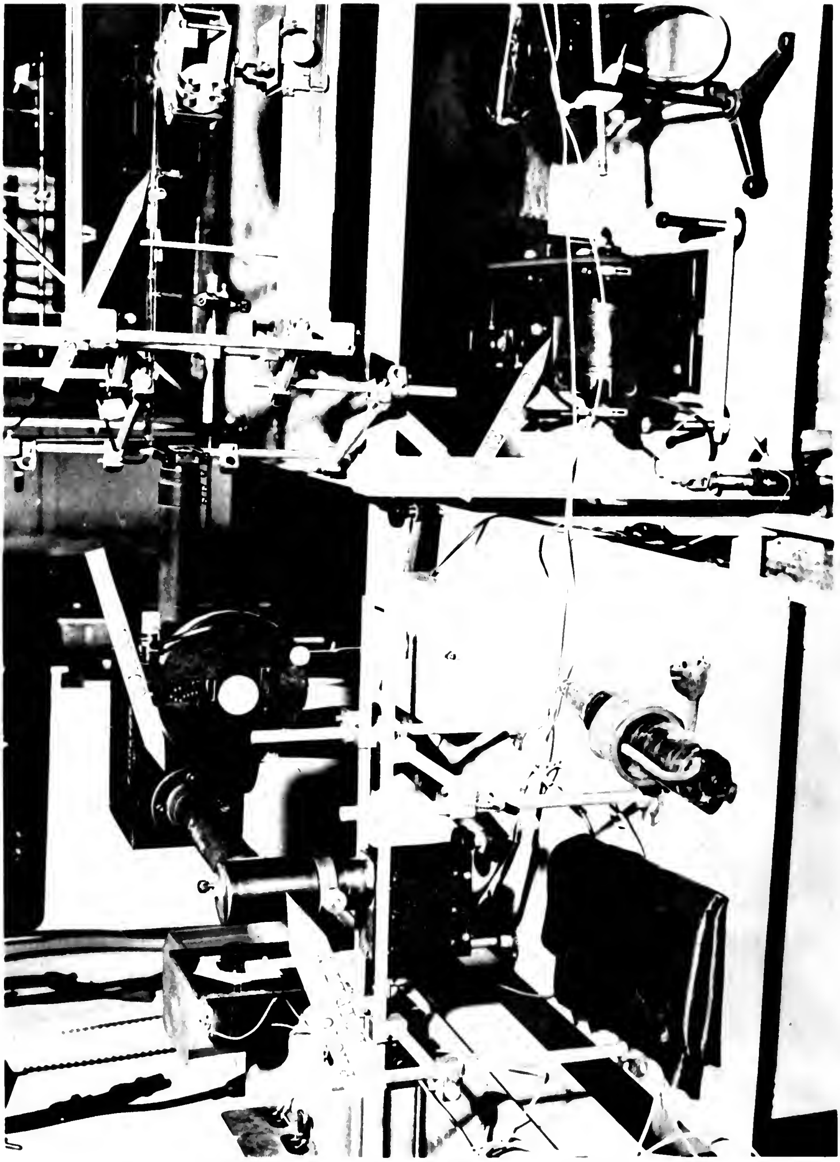
Consider three points in the positive column x_1, $x - \Delta x$, and x with x_1 nearest the cathode. Assume that there is a positive space charge peak at x, and that here the concentration of metastable atoms is low, but should rise to a maximum just on the cathode side of x; i.e., at $x - \Delta x$. Suppose that at this moment, however, the rate of production of metastable atoms due to collisions with electrons which have gained energy in the field of the positive space charge, is greatest still farther toward the cathode at x_1. This situation would exist if the electrons arriving at x_1 had energy just sufficient to excite the atoms to the metastable levels. At x_1, then, the rate of production of these metastable levels would be a maximum, and there would be little or no

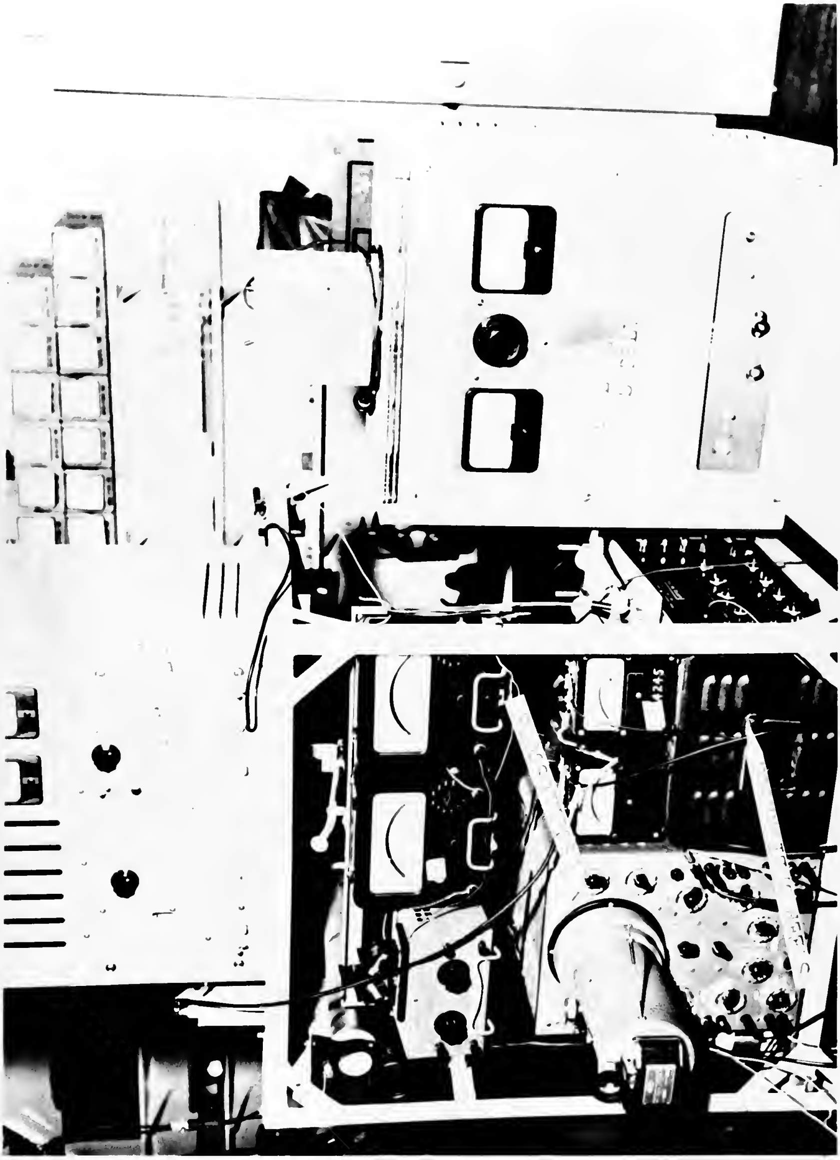
excitation to higher levels. Due to inelastic collisions at x_1 , the electrons would suffer a sharp drop in energy, but would gain energy again as they are accelerated toward the positive space charge concentration at x. When they get to $x - \Delta x$, where the concentration of metastable atoms is highest, they would begin to produce higher excited states and ions. Again having lost energy, the electrons would be accelerated toward x, but since the concentration of metastables there is low, there would be little or no ionization taking place. Thus at x, since no new ions are being formed, the ion concentration falls due to diffusion to the walls and recombination in the gas. On the anode side of x, the electrons will continue to lose energy in a negative field, and will therefore contribute no more excitation until picked up and accelerated by the following striation where the above process will be repeated all over again.

This mechanism just described, will (1) cause a concentration of metastable atoms to be built up at x_1 , (2) cause the ion concentration to rise and the metastable population to fall at $x - \Delta x$, and (3) cause the ion concentration to fall at x. This would then explain the motion of the positive striations toward the cathode.

One consequence of this theory should be that by spectroscopic studies, one should be able to locate the point x_1 where the rate of production of metastables is highest. Donahue and Dieke (6) have observed the mercury spectrum and found the 2537A line leading the other lines of the spectrum by about 15 usec. Mercury has a triplet 3P state at excitation potentials of 4.66, 4.86 and 5.43 volts, of which two are metastable, while the center one (4.86 volts corresponding to 2537A) is not metastable.

The other principal lines in the Hg spectrum, 5461, 4358, and 4047 have the same initial 3S state, with an excitation potential of 7.69 volts. They were found by Donahue and Dieke (6) to occur at the same instant on a time plot, and as mentioned earlier, were lagging the 2537A line by about 15 usec.





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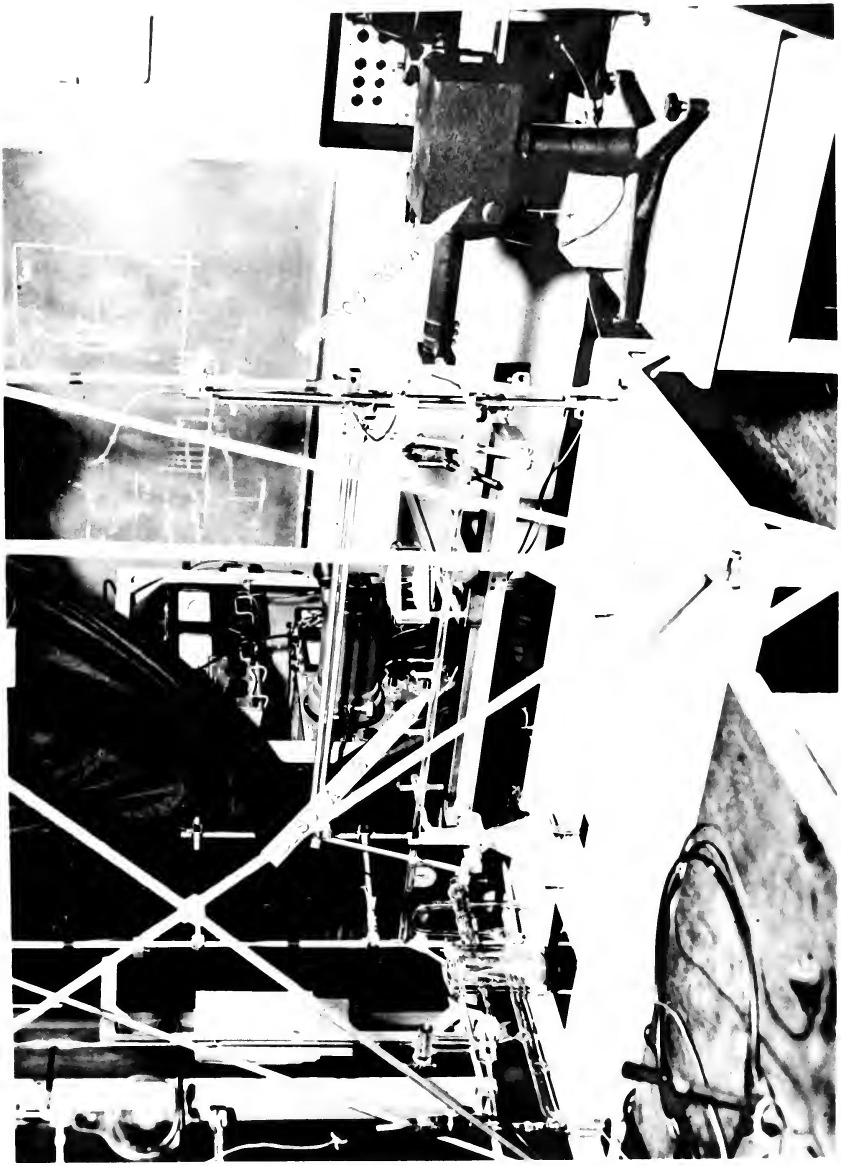
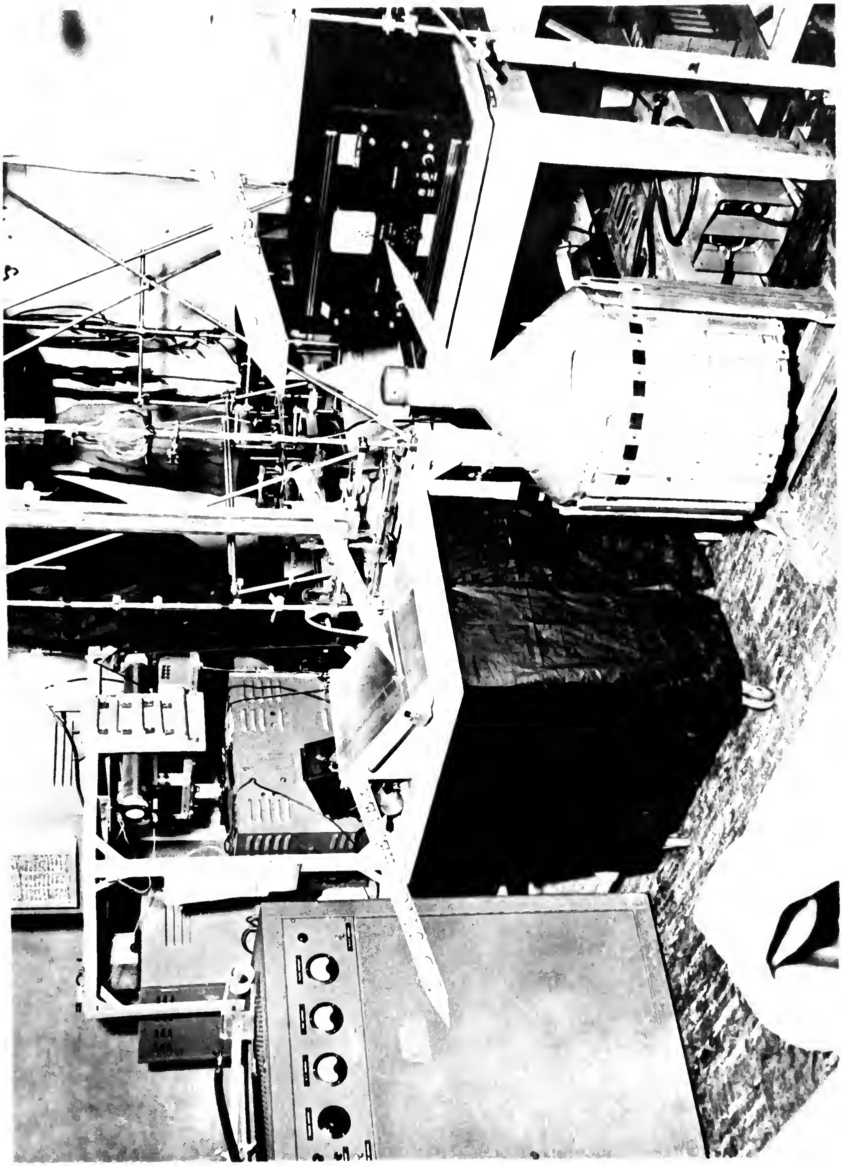




CHAPTER II

APPARATUS AND EXPERIMENTAL TECHNIQUES

1. General

The experimental techniques employed in this study were essentially the same as those used by Karge, Hooks and Oleson (10), who in turn patterned their techniques after Donahue and Dieke (5,6,7). One important difference, however, between the technique used in this study and that employed by Donahue and Dieke is that a glass prism monochromator was used for selecting the spectral lines, whereas Donahue and Dieke made use of a one meter grating spectrograph.

The entire vacuum system including the discharge tube was baked for extended periods of time by flaming and heating tapes, until an ultimate vacuum of 5×10^{-8} mm of Hg. was achieved prior to filling the discharge tube with argon. All units were operated for about a four hour warm up period prior to making any observations. Photographs of equipment and its physical arrangement are shown in Fig. 1,2,3 and 4.

2. High Vacuum and Gas Filling System

The vacuum system was of glass construction throughout and was mounted on a portable rack and table. This rack contained the discharge tube, the diffusion pump, liquid nitrogen traps, filling flask, manometer, and ion gauge. The forepump was mounted directly below this rack but supported separately.

This arrangement was designed by Professor N.L. Oleson, originally assembled by I.C. Dumas of the Stanford Research Institute, and is essentially the same as that used by Karge, Hooks and Oleson in previous studies of this subject at the Naval Postgraduate School. Necessary

modifications, repairs, and installation of the new discharge tube were accomplished by Professor S.H. Kalmbach.

The following is a description of the equipment associated with this system:

a. Welch Duo-Seal Vacuum Forepump.

b. Diffusion Pump, three stage, air cooled, type GF-25A using Octoil S Vacuum Pump Fluid, manufactured by Consolidated Vacuum Corp.

c. Ionization Gauge, Type DPA-38, manufactured by Consolidated Vacuum Corp.

d. Two liquid nitrogen traps in the system, one between the diffusion pump and the rest of the system, the second between the discharge tube and the rest of the system. The first trap was kept filled continuously, the second was filled only during the actual filling of the discharge tube with argon.

e. A one liter flask of Linde, high purity argon gas was sealed into the system. In the line leading to this flask were two stop cocks with a small bulb reservoir between, by means of which the discharge tube was filled with argon.

f. Gas pressures in the discharge tube were measured by means of a 100 cm. manometer filled with Octoil-S fluid. Both legs of this manometer were evacuated, then one leg was isolated by means of a stopcock, prior to admitting argon to the system.

g. Discharge tube—see separate description in Section 4 of this chapter.

A schematic of the vacuum layout is shown in Fig. 5.

3. Power Supply

A Sola type CSY-301495 Constant Voltage Transformer was used to supply regulated 60 cycle a.c. power to all electrical units. The output of this transformer was not a pure sine wave, but possessed a slightly squared off wave shape with a rms value of about 135 volts, and a constant peak value of 165 volts. This distortion, although not necessarily desirable, is not believed to have introduced any deleterious effects either to the equipment or to the investigation.

Power for the discharge tube was obtained from a Sorensen Nobatron Model 1000BB. This unit has a variable output voltage of 200-1000 volts D.C., with a maximum current rating of 500 milliamperes, and a D.C. output regulation of ± 0.5%.

Earlier attempts to use a G.E. Type YPD-4 Regulated Power Supply were unsuccessful due to poor regulation apparently caused by a defective filter in the output. A replacement spare was not immediately available, so this unit was abandoned, after the Sorensen Nobatron became available.

Power for the photo multiplier tube was supplied by a variable 500-1000 volt D.C. supply, with five 45 volt B batteries in series with it, so that variable D.C. voltages from 725-1225V volts were available. The photo multiplier tube was normally operated in the region of 1000-1200 volts.

4. Discharge Tube

The discharge tube was fabricated by I.C. Dumas of the Stanford Research Institute. This tube, shown schematically in Fig. 6, is constructed of Vicor glass tubing 1.3 cm O.D. with probes and electrodes

set in pyrex glass, and these in turn fused to the vicor with graded seals. The length overall is 101 cm. Electrodes are constructed of hafnium free zirconium and are movable, each electrode being capable of moving a distance of 12 cm. Movement is accomplished by means of glass enclosed magnetic slugs attached. Spiral lead-in wires of molybdenum provide the flexible connection from the electrodes to the end seals. The total distance between electrodes can be varied from about 34 cm. to 58 cm., and since both are movable, this provides the same feature as a movable probe with fixed electrodes. This feature was not used in this study, but the tube was built so that it would be available for future studies. All observations reported in this study were made with the electrodes 44.8 cm. apart.

5. Optical System and Photo Multiplier Tube

Light from any point in the discharge tube was focused by a pair of mirrors mounted on a carriage and traveling on a rack and pinion parallel to the discharge tube. Light from the mirrors passed through a condensing lens and was focused on the entrance slit of a Gaertner Model L231 Wave Length Spectrometer equipped with an exit slit. This converts the spectrometer into a monochromater with a range of 3950-8200 Å. Light from the exit slit of the monochromator fell on the photo sensitive surface of a 1P21 photo multiplier tube. The output current of the 1P21 photo multiplier was impressed across a 100,000 ohm resistance at the Y input terminals of one channel of the Dumont Type 322-A Dual Beam Cathode Ray oscilloscope.

6. Oscilloscope and Associated Equipment

A Dumont Type 322-A Dual Beam Oscilloscope provided the means of observing two wave forms simultaneously. The scope was operated with

sweep selector switch on position "A-common", so that both sweeps were supplied by the same sweep voltage and both were triggered by the same signal. The scope was triggered externally by the voltage oscillations across the discharge tube through a four microfared condenser. Thus the scope pattern shows the variation of light intensity from any point in the discharge tube with reference to the time of voltage maxima across the tube. The tube voltage variations were also impressed on the Y input of the other channel of the scope, so that direct comparisons were available. The schematic circuit diagram is shown in Fig. 7. In a similar manner the tube voltage oscillations may be compared with anode and cathode current variations using the circuits of Fig. 8 and 9, respectively.

A Browning Laboratories Model Gl-22A Sweep Calibrator was used to apply intensity modulated signals at 100 micro second intervals to the Z terminals of both channels.

A Hewlett-Packard Model 524A Frequency Counter was fed by the tube voltage variations and provided an instantaneous frequency indication.

A Dumont Type 295 Oscillograph Record Camera was used to photograph oscilloscope patterns. Kodak Ortho-Linograph film was used throughout at lens and shutter settings of F/2.8 and 1/37th second, respectively. Strip films obtained were later enlarged on a photo reader and analyzed. A double exposure technique was used whereby the first exposure was made with the vertical amplifiers off giving a zero voltage reference, then the second exposure superimposed the oscilloscope pattern being investigated. The 100 micro second markers were only displayed on the zero voltage reference, since they sometimes interfered with accurate determinations of phase on the wave forms.

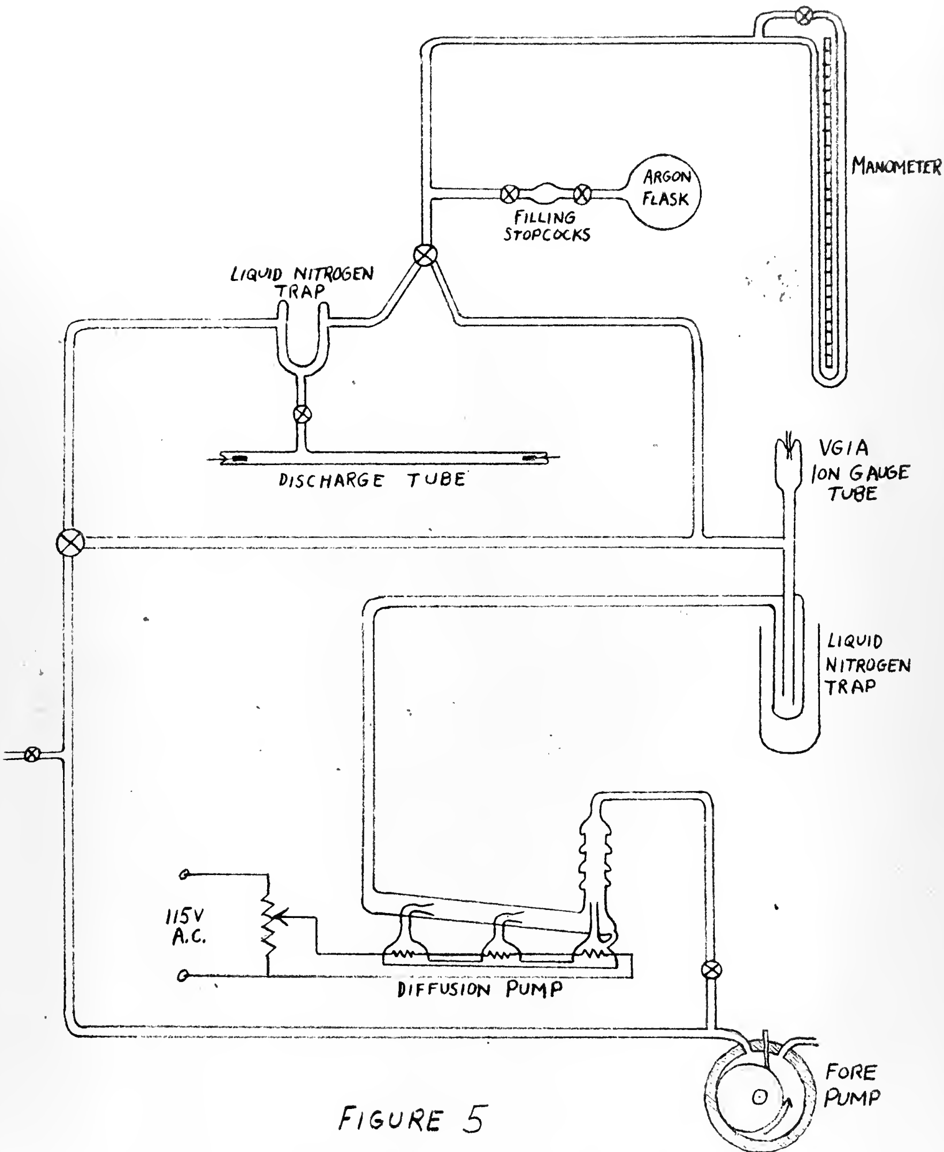


FIGURE 5

SCHEMATIC DIAGRAM OF VACUUM SYSTEM

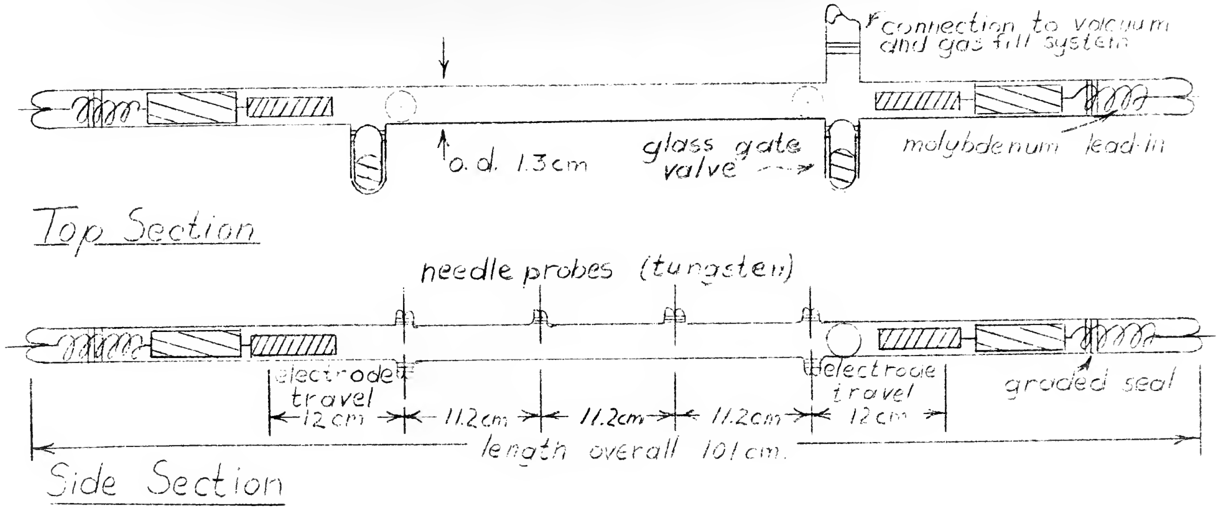


Fig. 6 : Details of Discharge Tube.

Tube proper of vicor glass fused to pyrex extensions by graded seals.

Gate valves closed while baking to protect tube from electrode spattering.

Moveable zirconium electrodes

Glass enclosed magnetic slugs

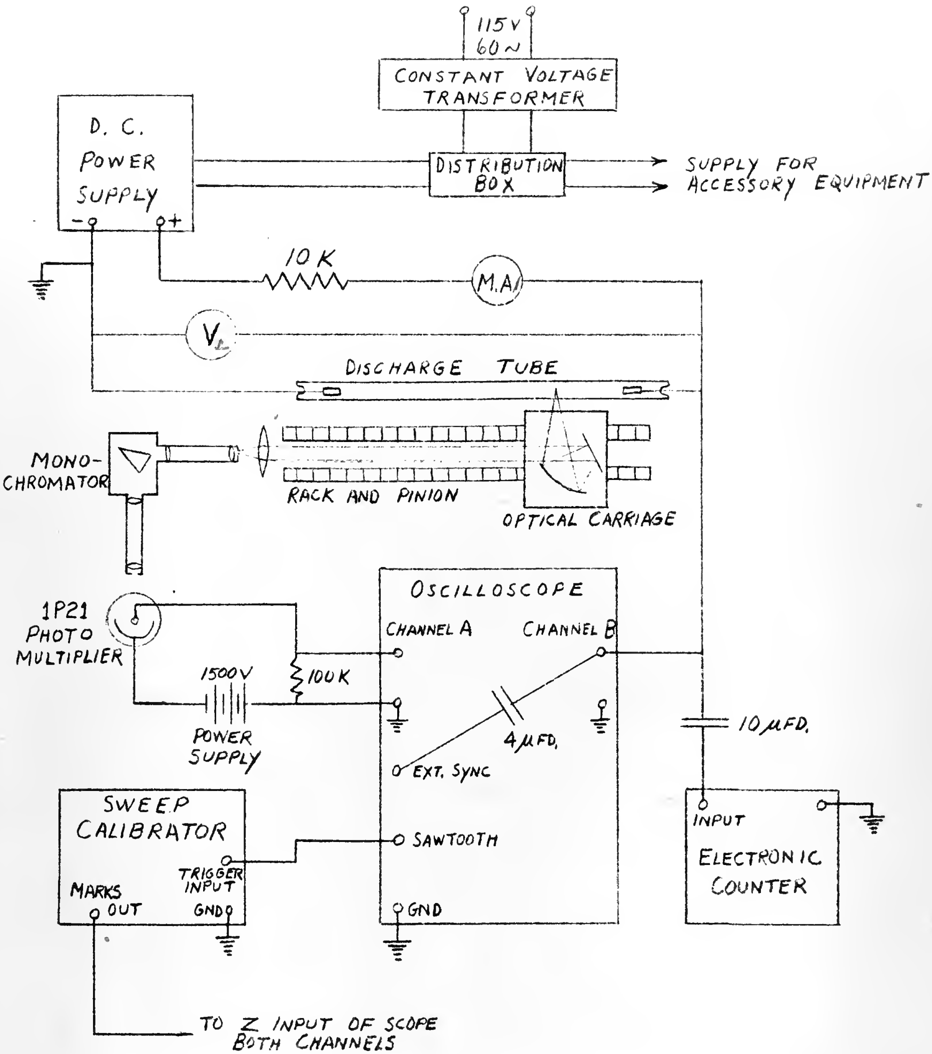


FIGURE 7

CIRCUIT FOR TUBE VOLTAGE - SPECTRAL INTENSITY OBSERVATIONS

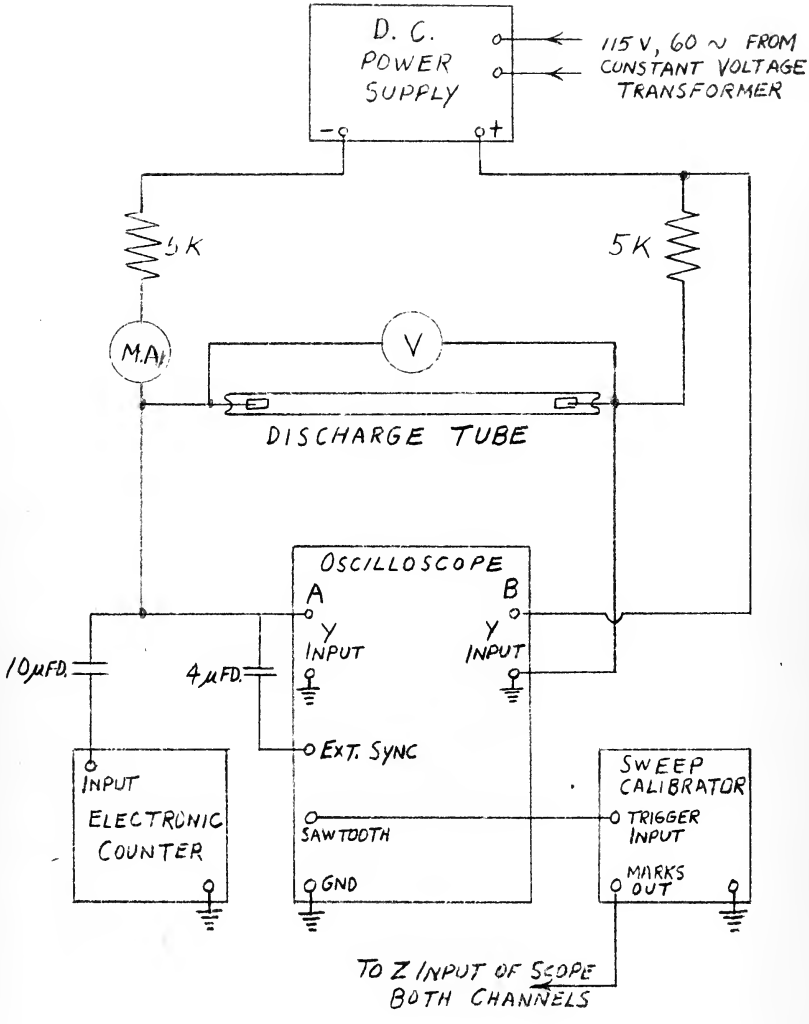


FIGURE 8

CIRCUIT FOR TUBE VOLTAGE - ANODE CURRENT OBSERVATIONS

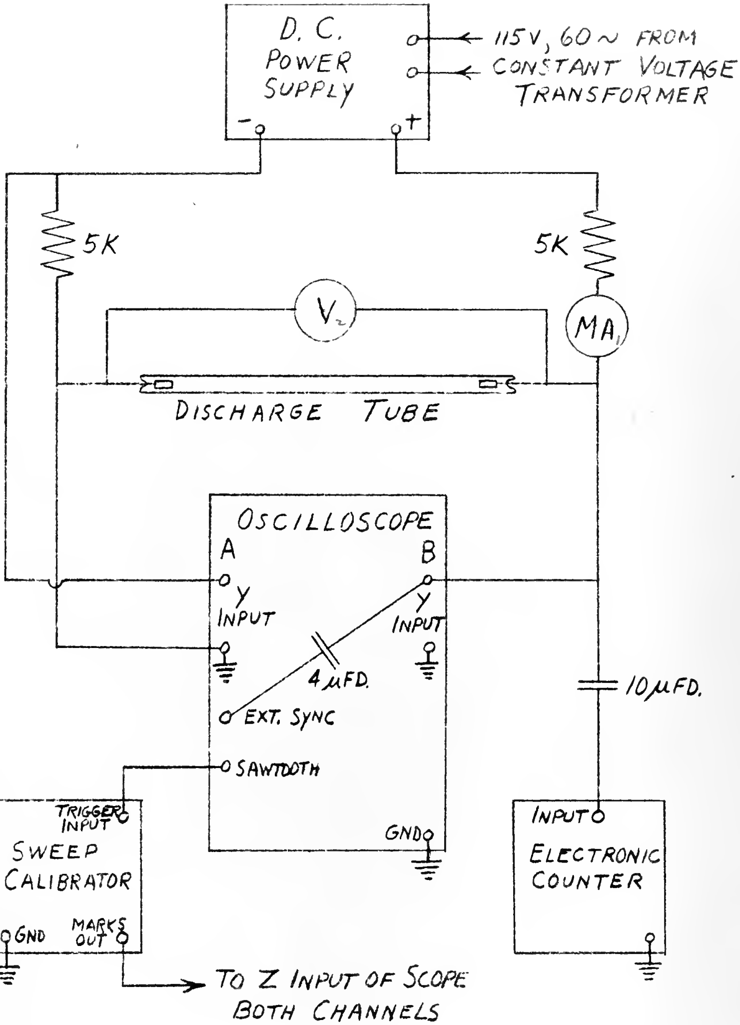


FIGURE 9

CIRCUIT FOR TUBE VOLTAGE - CATHODE CURRENT OBSERVATIONS

CHAPTER III

SOME ELECTRICAL CHARACTERISTICS

1. General

The electrical characteristics of a glow discharge in argon at 12 mm. of Hg. pressure have been studied by several persons in the past as noted in Chapter I. This particular investigation was undertaken to look into certain aspects that were noted by Karge and Hooks (10). On the basis of their oscillograph observations of tube voltage and tube current they had concluded that there was a phase shift between the tube voltage and current fluctuations. Further, they observed a possible phase difference between the current fluctuations at the anode and those same fluctuations at the cathode. This investigation studies, in particular, those voltage and current phase relations and at the same time, notes the other electrical characteristics of the discharge that were observed.

2. Procedure

The double exposure technique described in Section 5, Chapter 2, was used to record the oscillograph data produced by this experiment.

3. Phase Difference Between Tube Voltage and Current Fluctuations

Figs. 8 and 9 illustrate the circuits used for this investigation. With the circuit of Fig. 9, variations in tube voltage are amplified by channel A of the oscillograph and appear on the upper trace; cathode current variations, as produced by the voltage changes across a 5000 ohm resistor, are amplified by channel B and appear as the lower trace. With the circuit of Fig. 8, tube voltage and anode current fluctuations appear on the upper and lower traces, respectively. Either circuit will indicate

voltage and current phase relationships while a comparison of the observations from both circuits will indicate the phase relationships between anode and cathode currents.

Since the traces were displaced vertically from each other, it was necessary to have a vertical index in order to compare corresponding points of each trace. The vertical grid on the face of the scope was found to be unreliable for this, so a line connecting the leading edges of two corresponding 100 micro second time markers of each trace was used for this index.

The shape of the current fluctuation was generally not exactly the same shape as that of the voltage fluctuation. However, several peaks of the voltage trace could be matched with corresponding peaks of the current trace. Measurement of the time difference between corresponding peaks did not lead to a unique value because differently shaped peaks in the same picture were displaced by different amounts.

Fig. 10A and B illustrate the phase relationships when the tube current is 36 ma. In Fig. 10A it is seen that the cathode current lags the voltage by a very small amount. Fig. 10B shows that the anode current also lags the voltage by the same small time difference.

Fig. 11 is a plot of the results of this measurement over the operating range of the equipment. The range of variation indicated by vertical lines at the various currents represents the variation in time difference among the different voltage and current peaks of one oscillograph picture. The differences were all small, ranging from zero to fifteen microseconds. The voltage fluctuations consistently lead the current fluctuations of both electrodes. The phase differences at each electrode are sufficiently

similar to those of the other electrode to conclude that there is no significant anode-cathode current phase difference.

4. Other Electrical Characteristics

The capabilities of the circuit permitted the study of tube characteristics in the range of tube current from 13 to 105 milliamperes. Within this region, two distinct modes of oscillation were observed. These two modes were separated by discontinuities in tube voltage, oscillation frequency and magnitude of voltage and current fluctuation. This was a very narrow region of instability. Under certain conditions, a third mode of oscillation appeared at the point where the discontinuities and instabilities had previously appeared. This was a very unusual mode in all respects and we shall discuss it separately for that reason. We call this mode the 'standing mode' because of the distinct standing striations seen in the positive column whenever it occurred.

The oscillograph pictures of Fig. 12 illustrate the character of the tube voltage and current oscillations. Fig. 12A illustrates the oscillations at a tube current of 15 ma. As the current was increased, adjacent peaks became slightly different so that at 27.6 ma. (Fig. 12B) there were two distinct striation shapes which alternate and each phase cycle has two pulses. There have still been only gradual and continuous changes in frequency, voltage, oscillograph trace appearance and magnitude of oscillation. At slightly higher tube current, around 30 ma., the characteristics changed abruptly to those of Mode II. Fig. 12C illustrates the appearance of Mode II at 50 ma. current.

Fig. 13 is a graph which illustrates the variation in phase and pulse frequency with changes in tube current. Within each mode of

oscillation a smooth variation results but there is an abrupt change between the modes.

Fig. 14 illustrates the variation in the D.C. voltage of the tube with changes in tube current. This curve was determined at several different times, three of which are plotted. Note that although the D.C. voltage characteristic of the first mode was little changed with time, there is a pronounced change in the D.C. voltage characteristic of the second mode. This change tended to flatten out the voltage slope initially recorded at tube currents above 65 ma.

Fig. 15 illustrates the variation in amplitude of tube voltage and tube current fluctuations with changes in tube current. The fluctuations were small at low tube currents and increased to about 2% voltage and current modulation at 30 ma. Except for the standing striations, it remained around this value throughout Mode II.

The standing striations had extreme characteristics in every regard. They appeared very distinctly in the positive column of the discharge under certain conditions when the tube current was in the small range between 29 and 32 ma. They were unusually stable. When they were observed, the pulse frequency was much higher than that of the other modes. The voltage and current oscillations resembled a sine wave (see Fig. 12D) and were twice the amplitude of the oscillations of the other modes. Their existence over a period of several weeks coincided with modulation difficulties in our power supply whereby a very small, 120 cps pulse was being introduced into the circuit.

5. Analysis

The results of this experiment indicate that there is no phase shift between the current oscillations at the anode and those at the cathode.

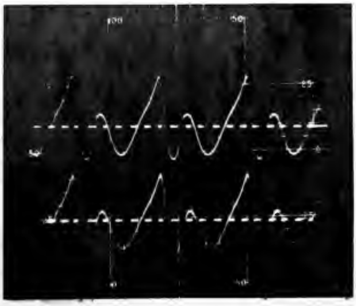
It appeared, however, that the current oscillations may lag the voltage oscillations by a small time period. The small magnitude of this delay and the fact that the magnitude was not consistent even for different points of the same trace may suggest that this delay was introduced by the circuitry rather than the characteristics of the tube.

In general, the other characteristics recorded were much the same as those recorded by Karge, Hooks and Oleson (10). In the same operating region, they noted one major and six minor points of discontinuity and instability separating eight different modes of oscillation. We recorded only two modes. Their major discontinuity was located very near the point that separated Modes I and II of our observations. It is believed that the difference between our observations and those made by Karge, Hooks and Oleson is primarily one of discrimination and definition.

Several additional observations were made from this data. The change in voltage characteristic of the second mode as the experiment progressed may be accounted for by a change in pressure within the tube. Leakage into the tube from the atmosphere may have caused a slightly higher pressure or leakage past the valve into the vacuum system could have reduced the pressure. The effect of small pressure changes on the character of moving striations could be the subject of an entirely separate study.

The characteristics of the 'standing mode' oscillations all suggest a resonance effect. They may have been caused by the small 120 cps pulses produced by the power supply during a certain period of the experiment. Their characteristics set them apart as a different phenomenon than the moving striations. The fact that they occurred at a point where there

had been an unstable, transition region between two oscillation modes is considered significant. It may indicate that the forces tending to produce the standing striations were less than those which produced the moving striations and hence the standing striations were formed only when the moving striations were poorly developed. Unfortunately, we could not produce the standing mode at a later time when light intensity studies were being made, so that the relationship between moving and standing striations could not be observed.



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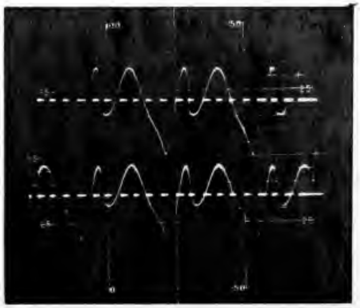


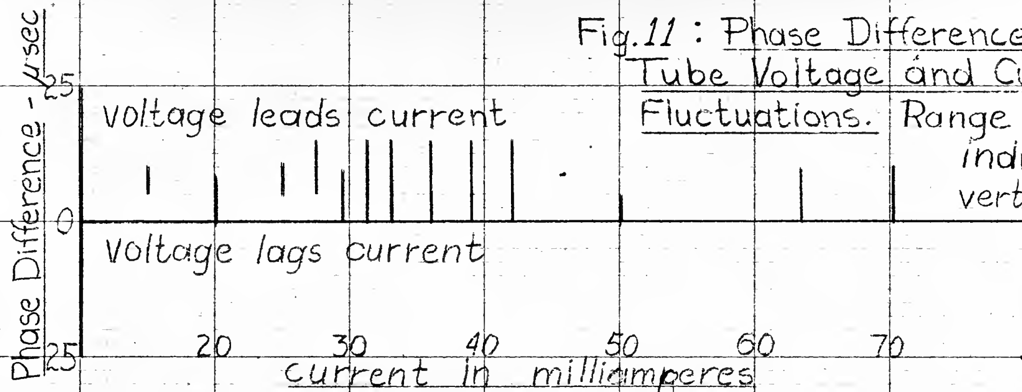
B

Figure 10. Phase Difference Between Voltage and Current Fluctuations.

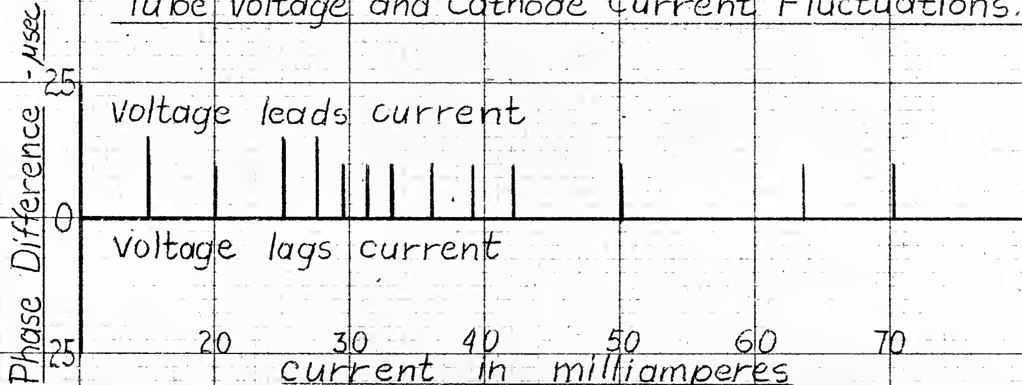
A. Upper trace is tube voltage fluctuation, increasing upward; lower trace is cathode current fluctuation, increasing downward; 36 ma.; 275 volts; 1579 cps.

B. Upper trace is tube voltage fluctuation, increasing downward; lower trace is anode current fluctuation, increasing upward; 36 ma.; 275 volts; 1580 cps.

Fig. 11 : Phase Difference Between Tube Voltage and Current Fluctuations. Range of variation indicated by vertical lines.



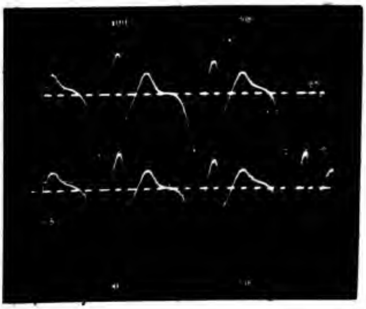
Tube Voltage and Cathode Current Fluctuations.

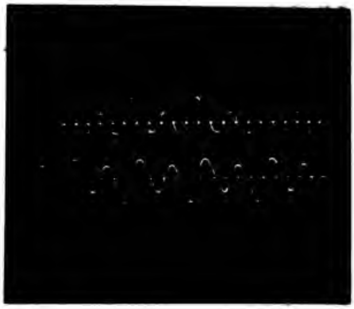


Tube Voltage and Anode Current Fluctuations.

A

B





C

D

Figure 12. Comparisons of Tube Voltage and Anode Current Fluctuations. Upper trace is tube voltage, increasing downward; lower trace is anode current, increasing upward.

A. Mode I, 15.1 ma., 290 volts, 3231 c.p.s.

B. Mode I, 27.6 ma., 270 volts, 1362 c.p.s.

C. Mode II, 50.0 ma., 264 volts, 1483 c.p.s.

D. Standing mode, 31.2 ma., 280 volts, 1880 c.p.s.

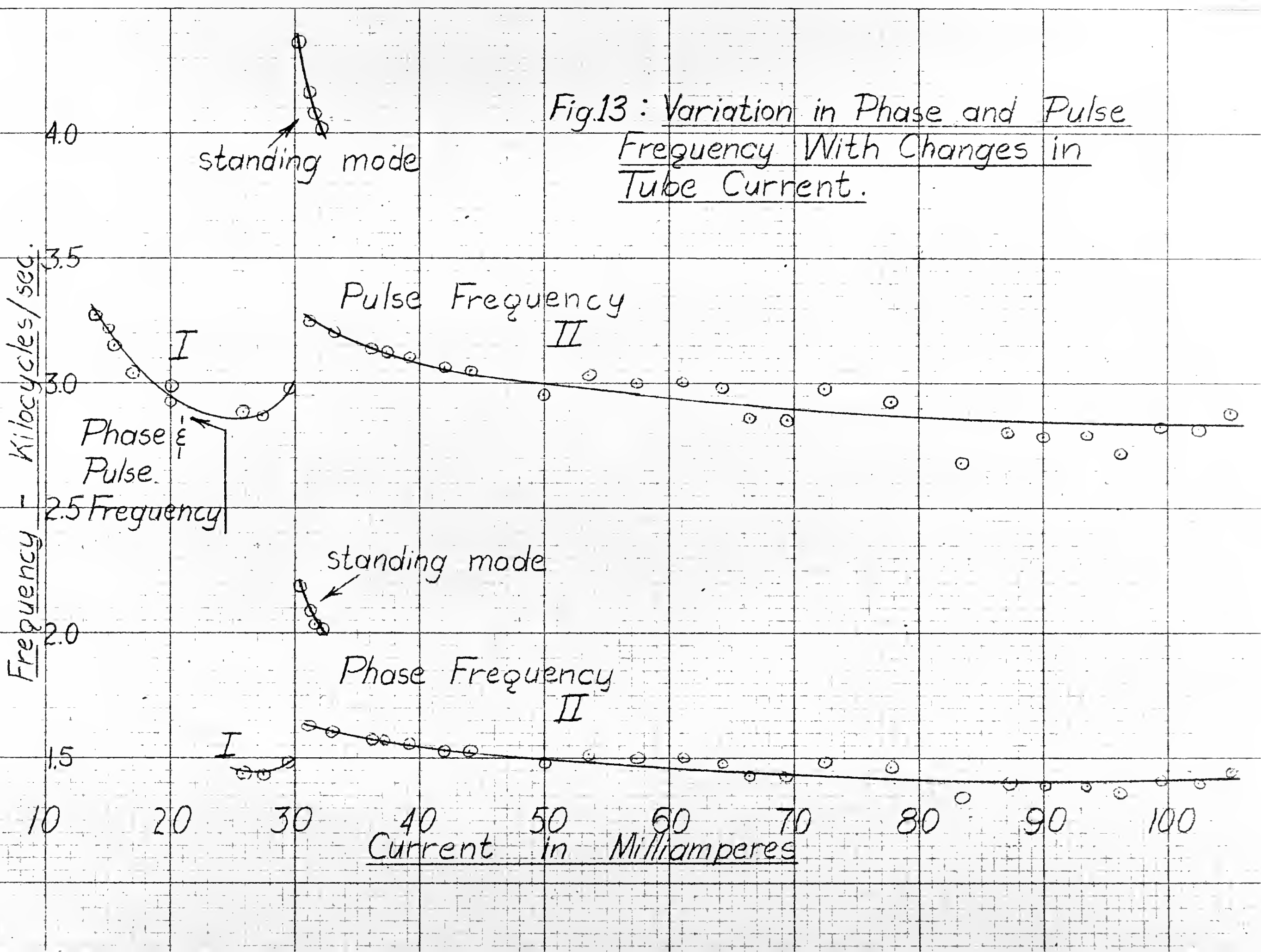


Fig.13 : Variation in Phase and Pulse Frequency With Changes in Tube Current.

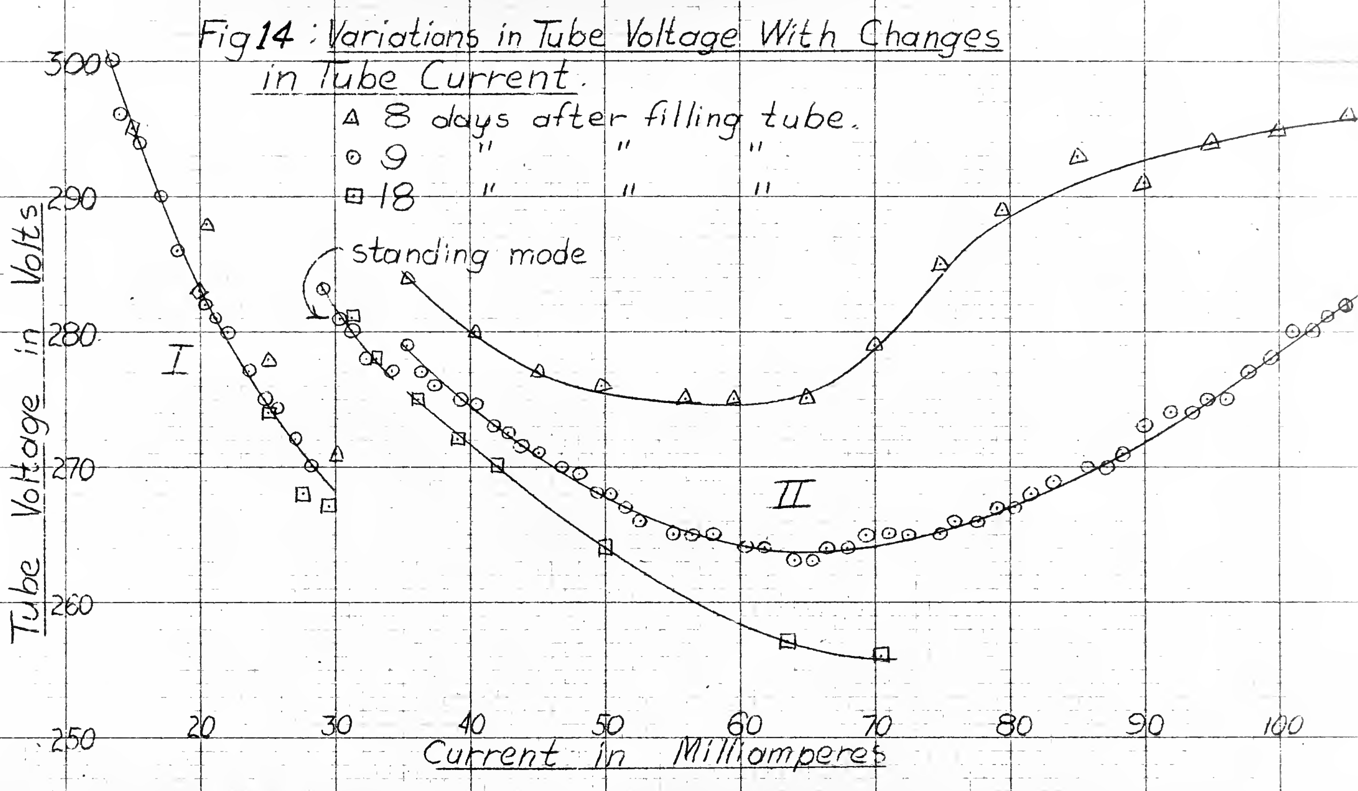


Fig 14 : Variations in Tube Voltage With Changes in Tube Current.
△ 8 days after filling tube.
⊙ 9 " " "
⊡ 18 " " "
standing mode
I
II
300
290
280
270
260
250
20
30
40
50
60
70
80
90
100
Tube Voltage in Volts
Current in Milliamperes

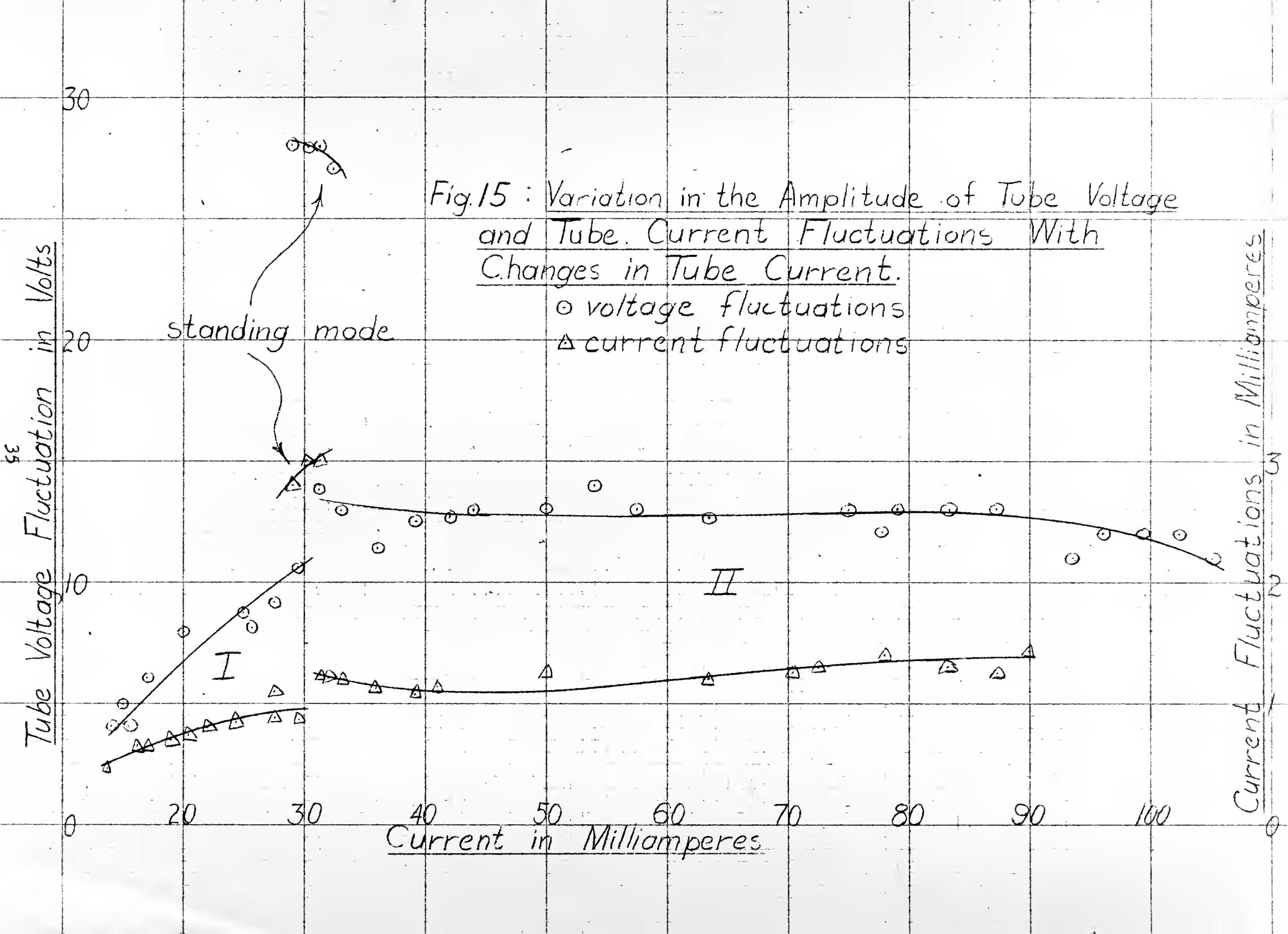


Fig. 15 : Variation in the Amplitude of Tube Voltage and Tube Current Fluctuations With Changes in Tube Current.

CHAPTER IV

SPECTROSCOPIC OBSERVATIONS

1. Spectrum Analysis

For this purpose both a quartz and a glass prism spectrometer, with photographic attachments, were used, and spectrums of the argon discharge were obtained on photographic plates along with a comparison spectrum of a mercury-cadmium arc. The discharge tube was operated at a current of 25 milliamps.

After developing, the plates were run through a microscope comparator, and a Russell-Shenstone first correction curve was plotted. From this the wave lengths of the most prominent lines in the argon spectrum were determined. The results obtained with the quartz monochromator did not reveal the presence of any lines in the near ultra violet with sufficient intensity to use, so that studies were confined to those lines in visible and near infra-red. Part of the energy level diagram of argon was plotted and appears in Figure 18 (in pocket inside of back cover). The data for this was obtained from "Atomic Energy Levels [12] by C.E. Moore of the National Bureau of Standards", and from "Atomic Energy States [3] by Bacher and Goudsmit of the University of Michigan". The particular energy level transitions were determined for the lines whose wave lengths were measured, and are tabulated in both Figures 16 and 18.

The first levels above the ground state in argon are the four 4S levels, two of which are metastable, namely $4S_5$ and $4S_3$. Unfortunately, the transitions from the other two levels, $4S_4$ and $4S_2$, to the ground state have wave lengths of 1066A and 1048A, respectively, and are far out

of the range of detection and analysis with the equipment available. Hence, it is not possible to locate the point x_1 , where the rate of production of metastable atoms is greatest. (See discussion of Donahue and Dieke (6) theory in Section 4, Chapter I). However, the location of the point on the cathode edge of $x - \Delta x$ would be indicated by a maxima in the 4P to 4S transitions. The transitions from 5P to 4S should indicate a point also in $x - \Delta x$ but nearer the anode. If the Donahue and Dieke (6) theory regarding the mechanismsof the motion of positive striations is correct, this second point should occur later in time than the first.

2. Spectral Line Phase Measurements

There were several difficulties involved in measuring the phase relationships of a number of spectral lines ranging in wave length from 4158A to 7635A. There were no photomultiplier tubes that cover this range entirely with a satisfactory sensitivity. Furthermore, since only one spectral line from a given point in the tube could be selected and fed to the oscilloscope at the same time, it was necessary to measure the time of a prominent point on the trace of each spectral line relative to some time reference point.

In order to produce a satisfactory sensitivity over the range of the spectrum, two photomultiplier tubes were used. Both tubes were 1P21 vacuum type photomultiplier tubes with slightly different spectral response. Several of the lines could be measured with both tubes and thus provided us with a check to insure that the use of different tubes was not introducing an error.

Figure 7 illustrates the circuit used for this phase of the experiment. The photomultiplier output was connected into one amplifier of the

oscillograph. The voltage across the discharge tube was connected into the other amplifier of the oscillograph and a prominent peak of the voltage trace was used for a time reference. In addition, tube voltage was used to sync both sweeps. The light intensity of each line, when placed on the oscillograph, always had exactly the same frequency as the tube voltage trace. The two traces were not always stationary to each other, however, there being momentary jumps in time and a gradual drift between them. These were small, but enough to be noticed on the scale of time that we were measuring. Eventually, stable operation of equipment and rapid completion of the runs eliminated the small time jumps and reduced the drift between the voltage and spectral intensity signals to an insignificant value.

The runs were conducted in the following manner. The wave length dial of the monochromator was adjusted for maximum intensity of the shortest wave length line. The oscillograph face was photographed. Quickly, the monochromator was adjusted to the next line; the face photographed; and so on until all the lines had been recorded and the monochromator was adjusted for the 7635A line. The process was repeated several times, as rapidly as possible. The photomultiplier tubes were exchanged as necessary to produce the required sensitivity.

As indicated in Figure 16, several lines occurred in pairs with wave lengths so close that the system did not have the necessary resolving power to separate them, and they were considered single lines. This was not the fault, particularly, of the system, but due to having to sacrifice resolving power in order to get sufficient illumination.

With this procedure, five photographs of the traces of the short wave length lines (1 - 5 in Figure 16) alternated with five photographs of the long wave length lines (6 - 10 in Figure 16) and were obtained under identical operating conditions.

Runs were conducted with the optical system focussed on a point in the positive column ten cm. from the anode. Tube current was 28 milliamps, tube voltage 274 volts, striation frequency 2719 c.p.s., wave length 3.15 cm.

3. Results

An analysis of the photographs indicated that the maxima of lines 1-5, representing transitions from the 5P to 4S states, occurred consistently at the same point in the cycle with the accuracy of the measurement estimated to be about four microseconds. Similarly, the maxima of lines 6-10, representing transitions from 4P to 4S, also occurred at the same time, but earlier than the maxima of lines 1-5 by about 15 microseconds.

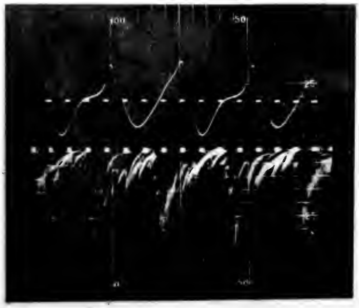
Figure 17 contains photographs of oscilloscope traces of tube voltage and spectral intensity. The arrangement of the circuit was such that increasing tube voltage is in an upward direction, while increasing spectral intensity is in a downward direction. The phase difference of 15 microseconds is not obvious due to the size of the photographs.

It is noted further that the intensity dropped to zero between maxima. With this same equipment, Karge, Hooks and Oleson (10) found that the total or overall intensity did not fall to zero between maxima. This would also indicate that there is a phase difference between the individual spectral lines sufficient to cause the overall intensity wave form to appear somewhat less than 100% modulated.

SPECTRAL LINES OF ARGON

Line	Wave length in Air Angstroms	Atomic Transition	Excitation Voltage
1.	4158.59	5P6-4S5	14.53
	4164.18	5P7-4S5	14.52
2.	4198.32	5P5-4S4	14.57
	4200.67	5P9-4S5	14.50
3.	4272.17	5P7-4S4	14.52
4.	4300.10	5P8-4S4	14.50
5.	4333.56	5P3-4S4	14.69
	4335.34	5P2-4S4	14.68
6.	6965.43	4P2-4S5	13.33
7.	7067.22	4P3-4S5	13.30
8.	7383.98	4P3-4S4	13.30
9.	7503.87	4P1-4S2	13.48
10.	7635.10	4P6-4S5	13.17

Figure 16



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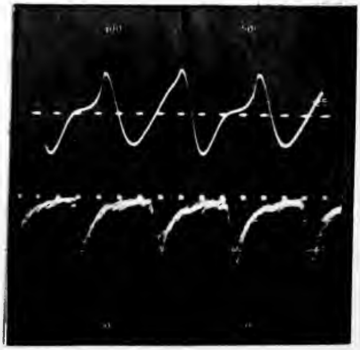

B

Figure 17. Spectral Intensity Fluctuations at 28 ma, 274 volts, 2719 c.p.s. Upper trace, tube voltage, 40 volts full scale, increasing upward; lower trace, spectral intensity, .1 volts full scale, increasing downward.

A. 4198A, 4200A

B. 6965A

The time difference between these lines is not apparent due to the very small magnitude involved.

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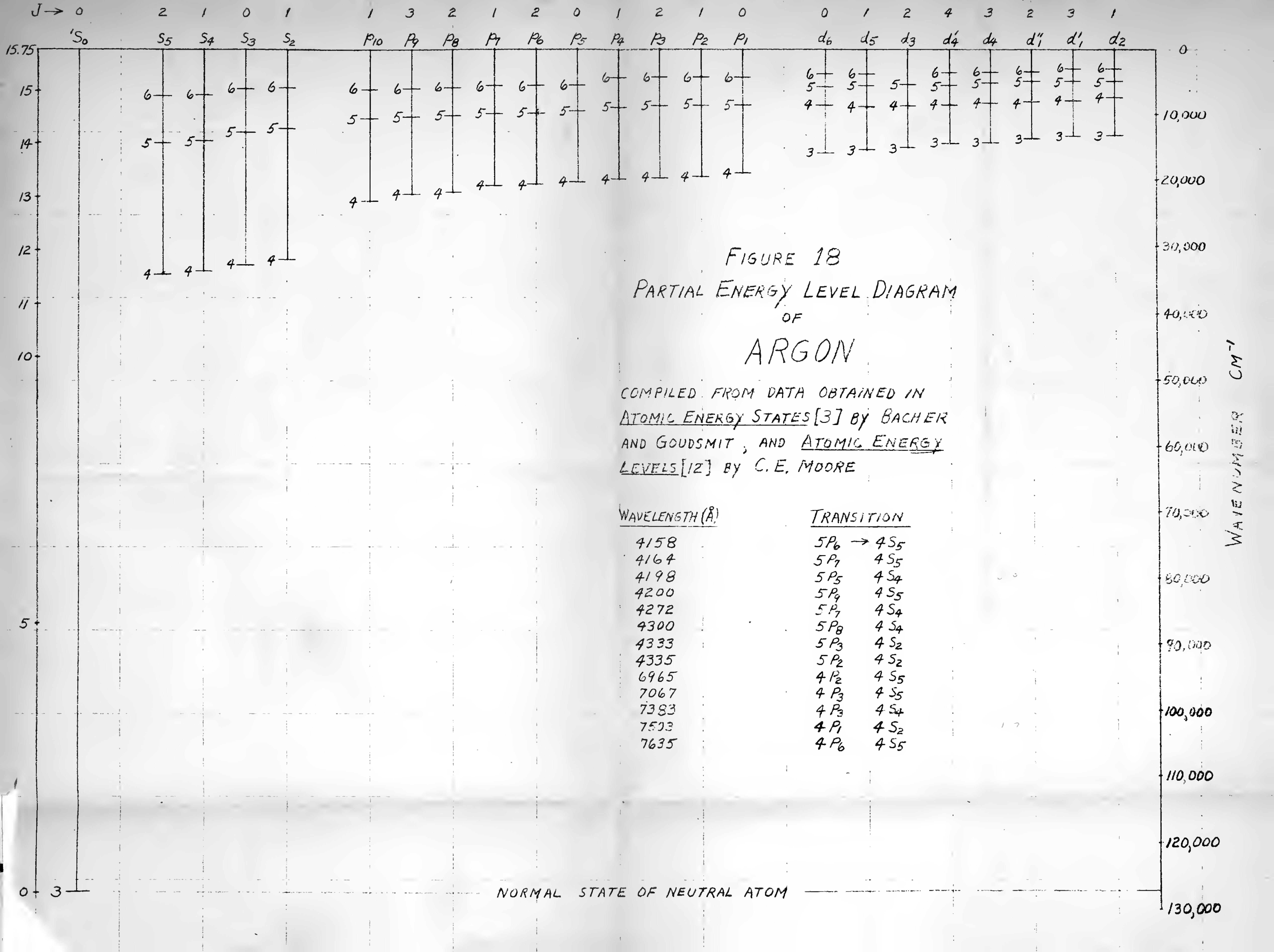

FIGURE 18

PARTIAL ENERGY LEVEL DIAGRAM
OF
ARGON

COMPILED FROM DATA OBTAINED IN <u>ATOMIC ENERGY STATES</u> [3] BY BACHER AND GOUDSMIT, AND <u>ATOMIC ENERGY LEVELS</u> [12] BY C. E. MOORE

WAVELENGTH (Å)	TRANSITION	
4158	$5P_6$ →	$4S_5$
4164	$5P_7$	$4S_5$
4198	$5P_5$	$4S_4$
4200	$5P_9$	$4S_5$
4272	$5P_7$	$4S_4$
4300	$5P_8$	$4S_4$
4333	$5P_3$	$4S_2$
4335	$5P_2$	$4S_2$
6965	$4P_2$	$4S_5$
7067	$4P_3$	$4S_5$
7383	$4P_3$	$4S_4$
7503	$4P_1$	$4S_2$
7635	$4P_6$	$4S_5$

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